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10/519900

DT05 Rec'd PCT/PTO 29 DEC 2004

SOLAR RECEIVER WITH A PLURALITY OF WORKING FLUID INLETS

FIELD OF THE INVENTION

The invention relates to a solar receiver designed for admitting concentrated solar radiation and converting its energy into another form of energy.

BACKGROUND OF THE INVENTION

A receiver of the kind to which the present invention refers typically has a housing with an interior space called a receiver chamber, and a window mounted in the housing to allow the concentrated radiation to enter the receiver chamber. The receiver housing also includes an inlet for the ingress into the receiver chamber of a working fluid which, when heated by the concentrated radiation, converts the heat into another form of energy. The working fluid may comprise components which, when heated, perform a chemical reaction. The receiver housing also comprises an outlet for the egress of the working fluid, possibly with the reaction products, from the receiver chamber. Examples of a solar receiver of this kind may be found in US 4,313,304 and WO 01/12314.

In a solar receiver as described above, it is desired that all the energy of concentrated solar radiation entering the receiver chamber be absorbed therein by the working fluid to allow the most efficient energy conversion. However, in practice, a part of the incoming radiation absorbed in the receiver chamber is re-irradiated back to the surrounding through the receiver aperture. The higher the temperature of the chamber walls, the more radiation is emitted thereby, increasing energy losses and thus reducing the receiver efficiency.

US 4,499,893 attempts to solve the above problem by ensuring that the working fluid together with chemical reactants comprised therein reach their maximal temperature and are withdrawn from the receiver chamber in the closest vicinity of the window. In the receiver of US 4,499,893 the window is mounted in an aperture formed in a front wall of the receiver chamber, inlet ports are arranged in side walls of the chamber for the ingress of the working fluid therein at locations remote from the window, and an outlet is in the form of an outlet opening in a rear wall of the chamber with a quartz exhaust pipe extending from the vicinity of the window through the outlet opening to the outside of the chamber. In consequence of this design, the working fluid is intended to absorb most of the radiation passing through the window in its vicinity just before the working fluid enters the exhaust tube so as to ensure that chemical reaction between the reactants of the working fluid take place inside the tube. Thereby, heating of the walls of the receiver is essentially reduced.

SUMMARY OF THE INVENTION

The present invention provides a solar receiver having a receiver chamber with a working fluid and a window at its front end, wherein measures are taken to ensure that the working fluid and, consequently, walls of the receiver chamber are heated to their highest temperatures at a region in the receiver chamber, which is relatively remote from the window and, preferably, has a relatively small cross-sectional area, whereas most of the chamber has temperature that is significantly lower and therefore re-radiation losses from the walls are substantially reduced.

In accordance with the present invention, this is obtained by:

- the provision in the receiver chamber of at least two inlet means spaced from said window and positioned at different distances therefrom for the injection into the receiver chamber of a working fluid characterized by a capability to absorb solar radiation; and

- the injection in said at least two inlet means of corresponding at least two flows of the working fluid such that the capability to absorb solar radiation of the flow of the working fluid injected via the inlet means located farther from the window is higher than that of the flow of the working fluid injected via the inlet means located closer to the window.

Consequently, heating of the working fluid to the highest temperatures occurs farther from the window, whereby re-radiation losses through the window are essentially minimized.

The meaning of the term *'spaced from the window'* used in the present application and claims with respect to the at least two inlet means is that the distance between said inlet means and the window is greater than that at which cooling or protecting fluid is normally directed along the window's surface to cool or protect the window, as for example, in WO 96/25633 or WO 01/12314.

The difference in absorption capability between the two or more flows of the working fluid entering the receiver chamber in accordance with the present invention may be obtained, for example, by the provision therein of different concentrations of particles which absorb solar radiation and get heated thereby to efficiently heat other components of the working fluid. In particular, in accordance with the present invention, the concentration of such particles in the working fluid flow entering the receiver chamber farther from the window is higher than in that entering the receiver chamber closer thereto.

In the receiver of the present invention, the concentration of particles in the different flows of the working fluid as well as the kind of such particles may be controlled automatically depending on working conditions.

In addition to the control of the concentration of the solar absorbing particles, it may be useful to have independent control of such parameters of the working fluid flows entering the receiver chamber as their rates and angles at which the flows are injected.

The effect of lowering energy losses by means of the invention is increased dramatically as the required overall operating temperature of the receiver increases.

Without being bound to theory, this may be explained by the known dependency of the re-radiation losses on the fourth power of the temperature:

$$\text{Reradiation losses} \sim \int \varepsilon\, T^4\, F\, dA,$$

wherein ε is the local emissivity of a wall area element dA, T is the local temperature of said area element, F is the view factor between said area element and the receiver aperture, and the integral is over the entire surface area of the chamber wall.

The exact values of the capability to absorb energy of the working fluid at its various entries to the receiver chamber may vary according to the shape of the receiver chamber, the working temperature and other working conditions of the receiver and the like.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be carried out in practice, a specific embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic illustration of a solar energy receiver according to one embodiment of the invention; and

Fig. 2 is a cross-section in the solar energy receiver of Fig. 1.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Fig. 1 shows a solar receiver **2** according to one embodiment of the present invention, adapted for the admission of solar radiation highly concentrated (up to several thousand suns) by a suitable solar concentrator (not shown), known in the art *per se*, for heating a working fluid (not shown) in the receiver, adapted for the operation under elevated pressures of up to about 20 atmospheres. The working

fluid, when heated is used for the conversion of its heat into another form of energy. This conversion may be performed in the receiver cavity, when heat absorbed by the working fluid initiates a chemical reaction between different reactants comprised in the working fluid. Alternatively, the working fluid after having been heated may be transferred to another site for the withdrawal of heat therefrom.

The receiver **2** includes a thermally isolated metal housing **4** with a receiver chamber **12** having a front wall **6,** a side wall **7**, a rear wall **8** and a longitudinal central axis A extending between the front and rear walls. The chamber **12** has a front region defined by the front wall **6** and the adjacent front half of the side wall 7, and a rear region defined by the rear wall **8** and the adjacent rear half of the side wall 7. As seen, the cross-sectional area of the rear region is smaller than that of the front region.

The front wall **6** is formed with an aperture **14** holding a window **16** for the admission of solar radiation and passing it into the receiver chamber. The aperture **14** is located in, or in the vicinity of, the focal plane of the solar concentrator. The window **16** may have any shape known in the art *per se*. It could be flat, if the pressure within the chamber were atmospheric or close thereto, but since this is normally not the case and the pressure within the chamber is higher, the window is preferably concave. It may also be shaped as an axi-symmetric dome, to improve its capability to withstand high temperatures such as about 500°C and higher. The window may also be frusto-conical and capped frusto-conical, or may have any other appropriate shape.

The solar receiver **2** has a plurality of inlet means **17** formed in the housing **4** for the injection of different flows of the working fluid into the receiver chamber **12** through inlet ports **17a, 17b, 17c** and **17d** formed in the side wall 7 of the receiver chamber **12.** The inlet ports **17a** to **17d** are all spaced from the aperture 14 to different axial distances $\mathbf{d_a}$ to $\mathbf{d_d}$ therefrom. The rear wall **8** of the receiver chamber is formed with an outlet port **18** for the withdrawal of the working fluid from the receiver chamber **12.**

The receiver further comprises means (not shown) for the provision of the different flows of the working fluid injecting into the receiver chamber **14** via the inlet ports **17a** to **17d**, with different absorption capability, particularly, with different concentration of solar absorbing particles. Such concentration control means are adapted to make sure that the concentration in the working fluid flows increases from its lowest value in the working fluid flow injected via the inlet port **17a** to the highest value in the working fluid flow injected via the inlet port **17d**, so that the absorption capability of the working fluid gradually increases with the increase of the axial distance from the window of the location of its injection. The concentration control means with which the inlet means **17** are connected may be in the form of different sources of working fluid having different parameters. Alternatively, the receiver may be associated with single source of working fluid free of solar absorbing particles or having some initial small concentration thereof, which single source is provided with a flow distributor for dividing the working fluid into a plurality of flows to be forwarded to different inlet means **17**, and with a source of solar absorbing particles, wherefrom particles are added to the different flows in different amounts, in accordance with desired values of concentration to be obtained in these flows.

It should be mentioned that with the working fluid comprising solar absorbing particles, the inlet port that is closest to the aperture **14** should still be spaced therefrom so as to minimize contact with the window **16** of the solar absorbing particles comprised in the working fluid flow injected therethrough.

It should be also mentioned that the receiver may further comprise an additional inlet means e.g. such as disclosed in WO 96/25633 or WO 01/12314 for the introduction along the window of a cooling or protecting flow of fluid. Clearly, this flow should be completely free of any solar absorbing particles.

The inlet ports **17a** to **17d** may further be provided with individual means for the independent control of other parameters of the working fluid flow therethrough, such as for example, the flow rate and the angle at which the working fluid is injected in the receiver chamber.

Fig. 2 illustrates one example of the design of the inlet means **17** and it shows a cross-sectional view of the receiver taken through one of the inlet means, i.e. that having inlet ports **17a**. As seen, the inlet means **17** includes a pipe **30** connectable to a source of the working fluid (not shown) providing a corresponding predetermined concentration of solar absorbing particles, a manifold **31** connected to the pipe **30** and a plurality of inlet nozzles **32** terminating at a plurality of the inlet ports **17a,** all in fluid communication with the manifold **31**. The inlet nozzles **32** have all different circumferential location and a substantially tangential orientation relative to the receiver chamber **12**. An angle **34** of the orientation of the inlet nozzles **32** may be independently controllable for each of the inlet means **17**.

The receiver chamber **12** is preferably elongated and converging towards the outlet port 18, however, generally, it may have any appropriate shape known in the art *per se*. It may be shaped as a cylinder, or cone, or a combination thereof, or it may be in the form of a dome, may have spindled or oval shape, or the like.

In operation, solar radiation enters the solar energy receiver **2** through the window **16.** The working fluid is injected into the receiver through the inlet means **17** in a plurality of flows while the concentration of the solar absorbing particles in different flows, and, optionally, also the rate of these flows and the injection angle **34,** are controlled at each of these means to achieve a maximal temperature of the working fluid at the rear region of the chamber. Consequently, the walls of the receiver chamber **12** have maximal temperature and maximal re-radiation at the rear region of the receiver chamber where the amount of re-radiation capable to escape through the window and, consequently, the heat losses in the receiver are minimal. Thereby, the energy-conversion efficiency of the receiver **2** may be essentially increased in comparison to the efficiency of a similar receiver having only one inlet means or having more than one inlet means, but all of them adapted to inject in a receiver chamber working fluid having the same solar absorption parameters.

EXPERIMENTAL RESULTS

Table 1 summarizes the test results from a few representative tests out of about 30, conducted separately with four different working gases in a receiver chamber of the kind to which the present invention refers. Both wall and gas temperatures were lowest near the aperture and increased with distance from it. Maximum wall and gas temperatures were measured near the gas outlet port. Table 1 shows only the temperature near the gas outlet port. As can be seen from the table, the measured temperatures were, in general, very high relative to those normally used in other solar receivers. In all cases, the exit gas temperature was higher than the temperature of the chamber rear wall adjacent the gas outlet port, demonstrating the non-isothermal effect described above.

Table 1. Selected test results

Gas	Wall temperature near gas outlet [K]	Exit gas temperature [K]	DT [K]	Particle Loading at Tg max [g/m3]
Ar	1720	1834	114	7.0
N2	1847	2079	232	3.8
N2	1748	2118	370	2.7
N2	1707	2008	301	3.5
N2	1836	1993	157	6.0
N2	1867	2017	150	5.3
N2	1792	1962	170	5.1
N2	1579	1887	308	2.4
N2	1651	1843	192	5.0
Air	1725	1903	178	4.5
CO2	1748	1878	130	4.7
CO2	1698	1789	91	5.3
CO2	1698	1744	46	2.1
CO2	1607	1659	52	6.2

Although a description of specific embodiments have been presented, it would be clear for a skilled person that variations could be made thereto without deviating from the major idea of the invention.